PRODUCTION OF HYDROGEN GAS FROM BIOMASS WASTES USING FLUIDIZED BED GASIFIER

A Thesis Submitted to the National Institute of Technology, Rourkela in Partial Fulfillment for the Requirements of Master of Technology (Res.) Degree

Submitted By
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CERTIFICATE

This is to certify that M.Tech. (Res.) thesis entitled, "**Production of Hydrogen Gas from Biomass Wastes Using Fluidized Bed Gasifier"** submitted by **Mr. Rajesh Tripathy** in partial fulfillments for the requirements of the award of Master of Technology (Res.) degree in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. He has fulfilled all the prescribed requirements and the thesis, which is based on candidate's own work, has not been submitted elsewhere.

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Mr. Rajesh Tripathy

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NOMENCLATURE

D	Screw outlet diameter, m
dp	Mean particle size, m
g	Acceleration due to gravity, m/sec^2
h	Fillet height ,m
H	Expanded bed height, m
H_{mf}	Bed height at minimum fluidization, m
H_t	Overall height, m
$\dot{m}_{bm}$	Mass flow rate of feed sample, kg/h
n	Speed of screw, rpm
TDH	Transport disengaging height, m
U_f	Fluidization velocity, m/s
U_t	Terminal velocity of particles, m/s
U_{mf}	Minimum fluidization velocity, m/s
S	Step of screw, m

GREEK SYMBOLS

ε	Particle porosity
φ	Sphericity
μ	Viscosity of air, kg/m.s
ρ	Density, kg/m^3

Subscript

f	Fluid
g	Gas
p	Particle

Abbreviation

S/B	Steam to biomass ratio
ER	Equivalence ratio
FBG	Fluidized Bed Gasifier
BM	Biomass

ABSTRACT

An energy efficient approach to hydrogen rich syn-gas production from biomass and wastes is represented at relatively low temperature, around 600^0C, in a continuous-feeding fluidized bed Gasifier. The effects of different biomass materials, temperature, steam to biomass ratio (S/B) and Equivalence Ratio (ER) on gas yield, gas composition, and carbon conversion efficiency have been studied. Higher temperature contributed to higher gas yield and carbon conversion. The steam introduction increased hydrogen yield by steam reforming and water gas shift reaction. Rice husk, rice straw and rice straw were gasified in the present work. Temperature during gasification was varied with 500-1000^0C. ER was varied within 0.15 to 0.35 and steam to biomass ratio was varied within 1.35 to 2.5. Minimum extra of 20% stoichiometric air is required for satisfactory performance of gasifier. ASPEN plus simulation was also carried out for optimization of process parameters. ASPEN plus simulation and experimental observations were found to have very good approximation in most of the cases. Performance of fluidized bed gasifier was satisfactory for ER within 0.25 to 0.35 and S/B ratio within 2 to 2.5.

Key words: Fluidized bed gasification, Syn-gas, Biomass, Steam to Biomass ratio, Equivalence ratio and ASPEN Plus Simulation

CHAPTER ONE

INTRODUCTION

1.0 Introduction

With increasing demand for energy, depleting primary energy sources (i.e. coal and oil) and detoriating environment, it has become essential not only to use the existing energy sources efficiently and thus conserve them, but also to develop alternate or non-conventional sources of energy. Although India produces about 35 million tons of crude oil, its import of crude oil is also increasing about 24 million tons as a result of increase in energy demand. So in order to alleviate India's dependence on import of oil, it is becoming increasingly clear that there is no option except to develop alternate or non-conventional sources of energy. Of the various renewable energy sources available, biomass appears to offer a promising solution to tackle the ever increasing energy demand (Basu, 2006).

Biomass is an organic matter produced by plants, both terrestrial (those grown on land) and aquatic (those grown in water) and their derivatives. It includes forest crops and residues, and animal manure. Biomass is the term used in the context of energy for a range of products which have been derived from photosynthesis. Thus everything which has been derived from the process of photosynthesis is a potential source of energy.

Biomass constitutes a significant, clean and renewable energy source and has very desirable option. Photosynthesis or photo-biological process is a continuous activity creating organic carbon that burns with less air pollution than fossil fuels. Photosynthesis helps to remove carbon dioxide from the atmosphere and generates oxygen, the life sustaining gas. Thus it helps to remove environmental pollution. Since plants use carbon dioxide for their growth, greater sources on biomass production may help to restore clean environment. Biomass energy is thus environmentally a very acceptable resource. In various types of Biomass samples, wood contains more calorific value, less ash content and the availability of wood is abundant.

Technologies to convert biomass in to energy fall two categories as mention below.

i. Bio chemical conversion (anaerobic digestion, fermentation) process

ii. Thermo chemical conversion (combustion and gasification) process.

1.1 Biochemical Conversion

Anaerobic digestion uses bacteria to break down organic wastes (animal manure, aquatic plants and etc.) in an oxygen free environmental to produce biogas (methane CH_4 and carbon dioxide CO_2 gas). The container system used (i.e. digester) varies greatly including single or multiple tanks, single or multiphase, batch, packed bed, expanded bed, mixed bed and variable bed systems. Efficiency of these systems is determined by the feed stock used, temperature required and most importantly quality of gas produced (less CO_2 the better). The effluent from the anaerobic digestion process also provides a valuable, fertilized product and contains less of its original odor.

Fermentation is the major process used to produce ethanol fuel. It involves enzymatic breakdown by micro-organisms at low pressure and low temperature. It causes the breakdown of complex molecules in organic compound under the influence of ferment such as yeast, bacteria, enzymes etc.

1.2 Thermo-chemical Conversion

Gasification and direct combustion are two examples of thermo-chemical conversion process. Direct combustion is probably the most common conversion process whereby solid biomass is burnt in a confined container, stove or boiler and combustion is maintained by airflow through the combustion chamber. Optimal airflow and properly dried biomass greatly enhance the efficiency of the combustion process.

Gasification is a process of turning solid biomass into combustible gas. The solid biomass is partially burnt in presence of air or oxygen to produce low or medium calorific value gases.Gasifier are very easy to operate, easyto maintainand reliable in operation.

1.3 Advantages of Biomass Gasification

Advantages of biomass energy utilization include ensuring the sustainability of energy supply in the long term as well as reducing the impact on the environment. As biomass energy uses agricultural waste as fuel, it is considered "CO_2 neutral" and emissions of sulfur dioxides and nitrogen oxides are very low, making it a good option as clean fuel for the environment. Indeed, among the technologies available for using biomass for producing electricity, gasification is relatively new. Gasification is primarily a thermo-chemical conversion oforganic materials at elevated temperature with partial oxidation. In gasification, the energy in biomass or any other organic matter is converted to combustible gases (mixture of CO, CH_4 and H_2), with char, water, and condensable as minor products. The concern for climatic variations has triggered the interest in biomass gasification making fluidized bed gasifiers as one the popular options, occupying nearly 20% of their market.

1.3.1 Advantage of FBG

(i) Fluidized Bed gasifier can handle all types of dry small sized biomass wastes.

(ii) It can be operated batch wise and continuous manner.

FBG handling biomass produces syn-gas of high colorific value and solid waste with less ash content. Time taken for ash conversion from biomass is less and density of char is less. Waste from agro industry, timber industry, sugar industry etc. can be used for power generation.

In rural areas, biomass samples are readily available for which power problem can also easily be solved with proper gasification technology.

1.4 Objectives

Objective of the present work has been framed in the following manner.

a) Design of FBG
b) Production of H_2 from biomass using FBG
c) Effect of biomass type on syn-gas composition
d) To study the effect of different parameters such as Steam to Biomass Ratio, Equivalence Ratio (ER) and temperature on composition of syn-gas.
e) To carry out ASPEN Plus simulation for further validation of the experimental data.

1.5 Thesis Outline

The present work has been documented in the form of a systematic report. The thesis report comprises the following chapters.

i. Introduction
ii. Literature Survey
iii. Designing Fluidized Bed Biomass Gasifier.
iv. Materials and Methods with Energy Calculation
v. ASPEN Plus Simulation, Experimental Observations and Results
vi. Discussion and Conclusion

CHAPTER TWO

LITERATURE SURVEY

2.0 Biomass Energy Conversion

Biomass is abundantly available in all parts of the world. Need for environmentally clean energy demands the use of biomass as an alternative source for renewable energy for which the biomass is to be converted by special technologies.

There are mainly two methods commonly used for biomass energy conversion

i. Direct Combustion (Incineration)

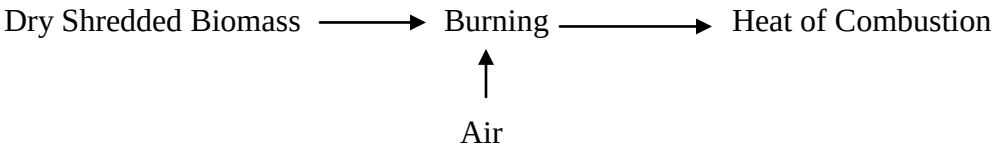
ii. Gasification

2.1 Direct Combustion of Biomass (Incineration)

Combustion is the process of burning (rapid oxidation accompanied by heat and light). Combustion also includes slow oxidation accompanied by little heat and no light. Incineration is the process of burning completely to ashes. The process of combustion is applicable to solid liquid and gaseous fuels. Combustion or burning is one of the most common processes in energy technology and biomass conversion technology. Generally the combustion process is applied to solid fuels including cultivated biomass and waste biomass. It is convenient and economical to burn the solid, semi-dried biomass and obtain useful heat at the location of biomass source (e.g. trees can be burnt at a site in the forest; sugar cane bagasse can be burnt near a sugar factory site). The heat obtained from the combustion of biomass can be used for several useful processes such as cooking, industrial heat requirements, steam generation, generation of electrical energy from steam etc. However, when the energy is to be transported over a long distance, it is more economical to convert the biomass into liquid or gaseous fuels and then transport them through pipeline or by tanks and use the fuels in liquid or gaseous forms at the receiving end. Alternatively the biomass is converted to electrical energy in a biomass thermal electrical power plant and the energy is transmitted in electrical power to the load center (Corella et al. 2007).

The applications of biomass combustion process cover a wide range of ratings from a fraction of kilowatt (for cooking) to a few megawatts (in municipal waste-to-energy electrical power plant).

The energy route of combustion process is:



2.2 Gasification

A solid fuel is converted by a series of thermo-chemical process like drying, pyrolysis, oxidation, and reduction to a gaseous fuel-synthesis gas. If atmospheric air is normally used as the gasification agent, the synthesis gas consists mainly of carbon monoxide, carbon dioxide, hydrogen and oxygen. A typical composition of the gas obtained from wood gasification on volumetric basis is as follows (Rai.2007).

Carbon monoxide	18 - 22%
Hydrogen	13 - 9%
Methane	1 - 5%
Heavier hydrocarbons	0.2 - 0.4%
Carbon dioxide	9 -12%
Nitrogen	45 - 55%
Water vapor	4%

The above mentioned gas can be used for generation of power either in dual fuel engines or in diesel engines with some modification. A spark ignition system engine (e.g. petrol engine) can be made to run entirely on synthesis gas, whereas those using compression ignition systems

engines (e.g. diesel engine) can be made to operate with about 60% - 80% fuel oil replacement by the gas. In larger systems, the gas can be burnt directly (e.g. industrial oil fired boiler).

As mentioned earlier, complete combustion takes place with excess air or at least 100% theoretical air, whereas gasification process takes place with excess carbon. The gasification of solid fuels containing carbon is accomplished in an air sealed, closed chamber under slight vacuum or pressure relative to ambient pressure. The fuel column is ignited at one point and exposed to the air blast. The gas is drawn off at another location. Depending upon the positions of air inlet and gas withdrawal point with reference to the fuel bed movement, three types of gasifiers have been designed and operated to date. They are as follows: (a) up-draft gasifier, (b) down-draft gasifier and (c) cross draft gasifier.

The advantages of a gasifier are:

i. It is very easy to operate the gasifier
ii. Its maintenance is easy
iii. It is simple in construction
iv. Reliable in operation

2.3Various Zones of Gasifier

The process of gasification taking place in various zones is distinguish and represented by the variation of temperature and the process carried out in each zone. The zones are classified as:

1. Drying zone
2. Pyrolysis zone
3. Reduction zone
4. Oxidation/ Combustion zone

The reactions taking place in different zones are also required to be discussed. They are as follows. Gasification involves a series of endothermic reactions supported by the heat produced from the combustion reaction. Gasification yields combustible gases such as hydrogen, carbon monoxide, and methane through a series of reactions. The following are four major gasification reactions (Basu, 2006).

1. Water gas reaction
2. Boudouard reaction
3. Shift conversion
4. Methanation

Brief descriptions of the reactions in different zones are given below.

2.3.1 Drying Zone

The main operation in drying zone is the removal of moisture. The temperature prevailing in this zone is 50°C-200°C. The radiant energy from the pyrolysis zone is the main energy for this zone. In general this zone occupies more volume of a gasifier.

2.3.2 Pyrolysis Zone

Water gas reaction is the partial oxidation of carbon by steam, which could come from a host of different sources, such as water vapor associated with the incoming air, vapor produced from the evaporation of water, and pyrolysis of the solid fuel. Steam reacts with the hot carbon according to the heterogeneous water gas reaction:

$$C + H_2O = H_2 + CO \qquad -131,38 \text{ kJ/kg mol carbon}$$

In some gasifiers, steam is supplied as the gasification medium with or without air or oxygen.

2.3.3 Reduction Zone

The carbon dioxide present in the gasifier reacts with char to produce CO according to the following endothermic reaction, which is known as the Boudouard reaction:

$$CO_2 + C = 2CO \qquad -172,\ 58\ kJ/mole\ carbon$$

2.3.4 Oxidation/combustion zone

Shift conversion and methanation are two major reactions taking place in this zone. The heating value of hydrogen is higher than that of carbon monoxide. Therefore, the reduction of steam by carbon monoxide to produce hydrogen is a highly desirable reaction.

$$CO + H_2O = CO_2 + H_2 \qquad -41,\ 98\ kJ/mole\ carbon$$

This endothermic reaction, known as water–gas shift, results in an increase in the ratio of hydrogen to carbon monoxide in the gas, and is employed in the manufacture of synthesis gas.

Methane also form in the gasifier through the following overall reaction:

$$C + 2H_2 = CH_4 \qquad +74,\ 90\ kJ/mole\ carbon$$

This reaction can be accelerated by nickel-based catalyst at 1100^0C and 6 to 8 bar. Methane formation is preferred especially when the gasification products are to be used as a feedstock for other chemical processes.

2.4 Classification of Gasifiers

Depending upon the bed movement, gasifiers are of two types i.e. fixed bed gasifier and moving bed gasifiers. Again according to the mode of contact of feedstock and gasifying medium the gasification system is classified in three categories as described in Fig.2.1. All these are as moving bed type gasifiers with different type contacts as follows:

1. Counter current (Up-draught)
2. Co-current (Down-draught)
3. Cross current (Cross-draught)

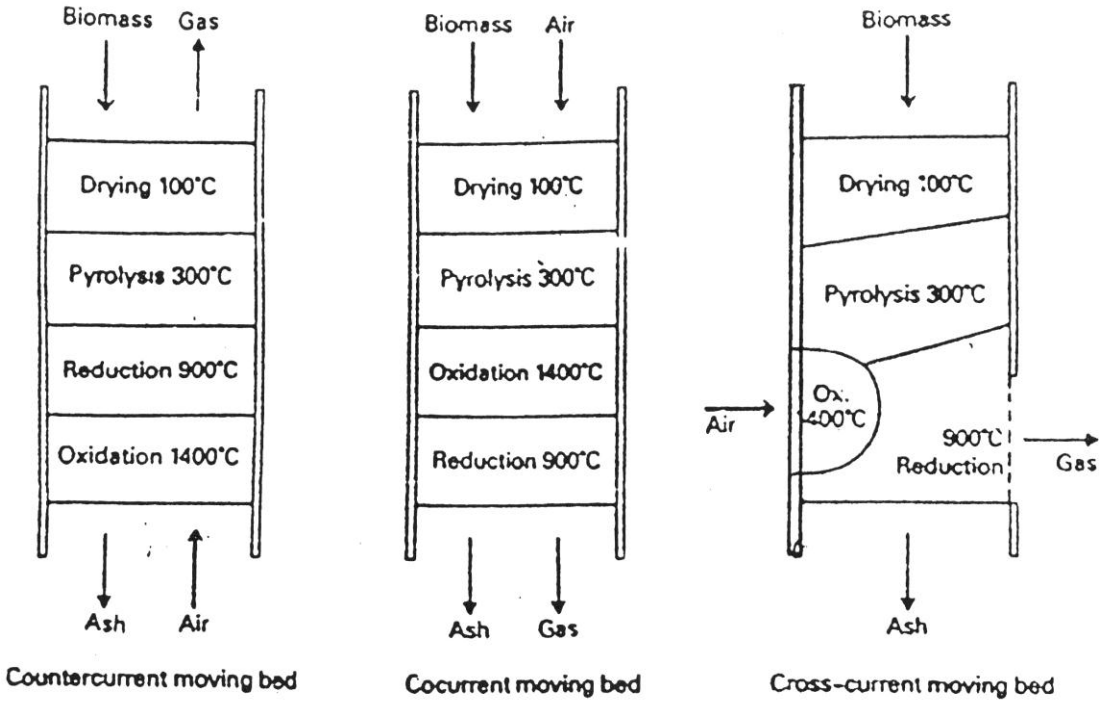


Fig.2.1 The schematic diagram of all these types of gasifiers

2.5 Fluidized Bed Gasifier

Again according to the conditions prevailing in the bed, moving bed gasifiers are classified as bubbling bed and fluidized bed gasifier. Since the fluidized bed allows an intensive mixing and a good heat transfer, there are no distinguished reaction zones. Hence, drying, pyrolysis, oxidation and reduction reactions take place simultaneously. The temperature distribution in the fluidized bed is relatively constant and typically ranges between 700°C and 900°C. The large thermal capacity of inert bed material plus the intense mixing associated with the fluid bed enable this

system to handle a much greater quantity and normally, a much lower quality of fuel(Li et al. 2004).

Fluidized bed Gasifiers are very easy to operate, easy to maintain, quick to start up, high combustion efficiency, high output, rapid response to fuel input changes, uniform temperature in the bed, low restart time, simple in construction and reliable in operation. Therefore the present work is focused on Fluidized Bed Gasifier.

2.6 Previous Work

Ramirez et al. (2007) suggested on the basic design of a pilot scale Fluidized Bed Gasifier for handling Rice Husk. According to them the gasifier was divided in seven parts or sub-systems intending to produce an energetic gas. Experimental tests conducted with such a gasifier showed that the developed procedure is adequate with a maximum deviation of 50% for the operational performance variables.

Kumar et al. (2009) modified steam and air fluidized bench-scale FBG. The effects of furnace temperature, steam to biomass ratio and equivalence ratio on gas composition, carbon conversion efficiency and energy conversion efficiency of the product gas were studied by them.

Murakami et al. (2006) discussed on some process fundamentals for biomass gasification in dual fluidized bed. The dual fluidized bed gasification technology is prospective because it produces high calorie product gas, free of N_2 even when air is used to generate the heat required for gasification via in situ combustion. The necessary process fundamentals for development of a bubbling fluidized bed (BFB) biomass gasifier coupled with pneumatic transported riser (PTR) char combustor were also studied by them.

Natarajan et al. (1998) determined agglomeration tendencies of some common agricultural residues in fluidized bed combustion and gasification system. It is observed that the combustion zone temperature is in the order of 900 – 1000^0C as in moving bed gasifiers and 800-900^0C in

fluidized bed gasifiers. The ashes of biomass feed stocks were observed to have ash fusion temperatures in the range of 800^0C to 1500^0C.

Rao et al. (2002) worked on thermo chemical characterization of various biomass samples using down draft gasifier and fixed bed and fluidized bed gasifiers. They observed that producer gas obtained is contaminated with tars, chars and ash particles to different degree depending upon the reactor type and feed stock utilized. The moisture content varies over a wide range from oven dry to about 90% on wet basis and ash content varies from 0.5 to 22%. Highest heating value of 12-18 MJ.N/m^3 was observed with producer gas.

Keijo (1995) studied co-combustion and gasification of various biomass samples using steam gasification. Wood based fuel and waste agricultural wastes, waste paper etc. were used for heat and power generation.

Schiffer et al. (1995) gasified different biomass samples including pulp and paper sludge to municipal sludge. They used high temperature winkler (HTW) process where solid feed stocks are gasified in a fluidized bed at elevated pressure using oxygen plus steam or air as gasification agents. They observed that biomass and waste materials often incorporate a higher amount of volatile matter, different proportions and compositions of inorganic matter having a significant variety of physical properties in comparison with coal. Therefore, gasification or co-gasification of peat, wood, sewage sludge has consequences with regard to feed stock preparation, gasification behavior, corrosion, emissions and residues. Thus, they recommended that HTW process is favorable for the conversion of Biomass.

Chern et al. (1998) used an empirical stoichiometric equation for wood chip gasification in a commercial-scale moving bed downdraft gasifier. The equation is based on an analysis of overall and elemental material balance for experimental data obtained with the gasifier. A thermodynamic analysis of the gasifier has also been performed. Resultant empirical efficiencies

of the gasifier have been evaluated for four different operating models at three different output temperatures. The resultant empirical stoichiometry was found to be in agreement with the experimental observations.

Warnecke (2000) carried out a comparative study on gasification process between fluidized and fixed bed gasifier using different feed samples. Other aspects such as technology involved in the process, energy consumption for the process, environmental problem caused by the process and overall economy of the process were also analyzed by him. It was concluded that there is no significant advantage with fixed bed gasifier or fluidized bed gasifier.

CHAPTER FOUR

MATERIALS AND METHODS WITH ENERGY CALCULATION

4.1 Materials

Different types of biomass are studied through proximate and ultimate analysis. These samples are used in gasifier for production of hydrogen. The materials are required to be sized for using in the fluidized bed gasifier.

4.1.1Collection, Sizing, Drying Of Biomass Sample and Bed Material

The following raw materials and bed materials have been used in the biomass gasification experiments.

Raw material (Biomass samples): Saw dust, Rice husk, Rice straw

Bed material: Sand

Fluidizing Medium: Air supply

Gasification Medium: Steam supply

Rice husk and saw dust were used directly in the gasifier as the available materials were of proper sizes. But Rice straws were sized to required size by cutting. The photographs of the samples are shown in Fig.4.1.

Fig. 4.1 Biomass sample used for experiment

4.1.2 Different Parts of Experiment Setup

A blower with controlling valve is used for continuous air supply. A bubble cap air distributer is provided at the bottom of gasifier. Two screw conveyers are provided, one for feeding the biomass and second one is for feeding the bed materials. Arrangement for LPG supply and firing point are also made. Three drainage points are located at different heights of the gasifier. Detailed explanations have already been discussed in Chapter-3.

4.2 Methods

4.2.1 Analysis of Physical Properties

There are some other properties like bulk density, mean particle size, sphericity and porosity which were required to be measured for experimentation. These were measured for the biomass samples, which are as shown in Table - 4.1.

Table - 4.1Physical Properties of Biomass and bed material was studied

Property	Mean particle size (mm)	Apparent density (kg/m^3)	Porosity	Sphericity
Bed material				
Sand	0.38	2650	0.44	0.77
Biomass				
Rice husk	0.53	426	0.81	0.37
Rice straw	2.6	153	0.46	0.56
Saw dust	0.81	244	0.7	0.45

4.2.2 Preliminary Analysis of the Biomass Samples

The following analyses have been carried out for the characterization of the different biomass samples.

- Ultimate analysis
- Thermo gravimetric analysis (TGA)
- Proximate analysis
- Analysis of other properties

4.2.3 Ultimate analysis

Determination of total carbon, hydrogen, nitrogen, oxygen and sulfur percentages in the biomass sample is carried out by its ultimate analysis. With the ultimate analysis for all these biomass samples, the following results as shown in Table - 4.2 were obtained.

Table-4.2 Ultimate Analysis

Types of biomass	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Oxygen (%)
Rice husk	38.45	4.96	0.82	0.18	55.59
Rice straw	36.6	4.55	0.47	0.21	58.17
Saw dust	45.78	5.32	0.18	0.07	48.65

4.2.4 Proximate analysis

Determination of moisture content, volatile matter, ash content and fixed carbon in the biomass sample is known as the proximate analysis. The proximate analysis results for different biomass samples give the following results which are listed in Table - 4.3.

Table - 4.3 Proximate Analyses

Biomass samples	Moisture content (%)	Volatile matter (%)	Ash content (%)	Fixed carbon (%)
Rice husk	7.34	56.37	15.83	20.46
Rice straw	9.38	69.53	3.04	18.05
Saw dust	8.8	87.57	1.94	16.45

4.2.5 Operating Procedure

Inert bed material is fed to the gasifier at first up to certain height. Biomass feed is fed continuously by the screw conveyer carefully. A specified quantity of water is added into steam generator for steam-generation. Feed stocks in the gasifier are then ignited by LPG to preheat the

bed material with in gasifier till the temperature reaches up to 550 - 600^{0}C. The temperature of the bed material within gasifier is increased gradually. By the time it reaches 800^{0}C steam starts pinching. When temperature at the neck and outer wall of furnace reaches 900^{0}C gasifying agents are driven into the gasifier and then the tests start up. The temperatures at 7 different locations at different intervals of test are recorded. The gas yield is measured by a flow meter simultaneously. Usually, the steady state is reached at around 15 minutes after startup and then gas sampling is carried out at an interval of 10 minute. Every operating condition is repeated twice to assure the reliability of the experimental results and the average of these observed values are considered as the experimental results.

4.2.6 Output Measurement and Scope of Experiment

The aim of the present investigation is to improve and optimize the gasification efficiency by varying the percentage of stoichiometric air and steam supply. Effect of equivalence ratio, reaction temperature and steam to biomass ratio on the production as well as the composition of syn-gas is also observed during the experimental work. Outputs from different biomass samples used as feed material are also analyzed for future improvement.

Scope of this experiment is aimed to

i. Improve the calorific value of syn gas/Increase the percentage of H_2 and CH_4
ii. Reduce the char content in solid waste
iii. Make the process more economical and eco friendly

4.3 Chemical Formula of Biomass

The calculation of chemical formula is important to determine the stoichiometric amount of air required for the combustion of the biomass samples. A sample calculation for finding the chemical formula Rice husk is discussed below (Roy, 1994).

Sample calculation for chemical formula of Rice Husk:

Weight of rice husk sample =12.34 mg

Analysis of Biomass (in wt %): C= 38.45%, H= 4.96%, N= 0.82 %, S= 0.18%, O= 55.29%

(A) Using the composition of rice husk found from Ultimate analysis, the amount of different elements in this sample are calculated as follows:

Amount of Carbon = (38.45×12.34)/100= 4.74

Amount of Hydrogen = (4.96×12.34)/100= 0.612

Amount of Nitrogen = (0.82×12.34)/100=0.101

Amount of Sulfur = (0.18×12.34)/100= 0.022

Amount of oxygen = (55.89×12.34)/100= 6.897

(B) Number of moles of different elements present in this sample is calculated as follows:

No. of moles of Carbon = 4.74/12= 0.395

No. of atoms of Hydrogen = 0.612/1= 0.306

No. of moles of Nitrogen = 0.101/14=0.0072≈0

No. of moles of Sulfur = 0.022/32= 0.000694

No. of moles of Oxygen= 6.89/16= 0.431

Hence the total no. of moles = 0.395+0.306+0.431+0.0072+0.000694=1.13989 ≅1.14

(C) Number of moles= mass/molecular weight

Mass= 12.34 mg, Number of moles =1.14

Thus, molecular weight = mass / no. of moles= 12.34/1.14= 10.82

(D) Amount of Carbon = (10.82×38.45)/ 100= 4.16mg

Atoms of Carbon = 4.16/12= 0.3467

Amount of Hydrogen = (10.82×4.96)/100= 0.5367 mg

Atoms of Hydrogen = 0.5367/2= 0.268

Amount of Oxygen= (10.82×55.59)/100= 6.015 mg

Atoms of Oxygen= 6.015/16= 0.376

Amount of Nitrogen = (10.82×0.82)/100 = 0.088724 mg

Atoms of Nitrogen = 6.015/14 = 0.0061

Amount of Sulfur = (10.82×0.18)/100 = 0.019476 mg

Atoms of Sulfur = 0.019476/32= 0.000608

Neglecting the N_2 and S content, the formula of biomass should be $C_{0.347}H_{0.5367}O_{0.376}$ Considering Carbon as the base for the carbonaceous material, the chemical formula is $CH_{1.55}O_{1.08}$. Similarly the chemical formula for rice straw and saw dust are calculated. The chemical formula for these biomass samples viz. rice husk, rice straw and saw dust with and without N, S are shown in Table - 4.4.

Table - 4.4 Chemical formulas of biomass samples

Biomass Samples	Chemical formula of Biomass	
	With N, S	Without N,S
Rice husk	$CH_{1.55}O_{1.08}N_{0.02}S_{0.02}$	$CH_{1.55}O_{1.08}$
Rice Straw	$CH_{1.49}O_{1.19}N_{0.011}S_{0.0021}$	$CH_{1.49}O_{1.19}$
Saw Dust	$CH_{1.392}O_{0.8}N_{0.0037}S_{0.00057}$	$CH_{1.39}O_{0.8}$

4.4 Energy Balance and Mass Balance Calculations

Based on the properties of the different biomass samples, the energy balance and mass balance calculations were carried out. A sample calculation has been given below (Basu, 2006 and Philippe et al., 2002)

Sample Calculation:

Biomass Fuel - 1 kg/hr

Steam – 0.117 kg/kg of biomass

Moisture is 8%

Specific Humidity of air 0.01kg of moisture per kg of dry air.

Composition of Rice Husk (weight %)

H = 4.96 %, C = 38.45 %, N =0.82 %, O= 55.59 %, S = 0.18%

Product Syn gas:

H_2 =12.28%, CH_4 = 2.60%, CO = 9.2%, CO_2 = 7.78%, N_2 = 50%

Let dry air be supplied at 2.771kg / kg fuel

HHV=16.2 MJ/kg

Basis: 1 kg of fuel 0.8kg moisture, 0.92kg dry fuel

4.4.1 Material balance:

Nitrogen

Air contains 76.9% N_2 by mass

So N_2 from air= 0.769 ×2.771 = 2.130 kg N_2/ kg BM

Total N_2 supplied by air and fuel which carry 0.82% N_2

= 2.130+ 0.0082 = 2.1390 kg N_2 / kg BM

= 2.1390/28=0.0763 kg mol / kg BM

We know cleaned gas contains 50% N_2.

Hence the amount of product gas produced

= 0.0763/ 0.5 = 0.1528 kg mol N_2gas / kg BM

Oxygen

Oxygen supplied to gasifier is (with air)

= 0.2315 ×2.771= 0.6414 kg/kg BM

Steam supplied = 0.117 kg /kg BM

So oxygen associated with steam supply

= 16/18 *0.117 = 0.104 kg /kg BM

Moisture in biomass feed = 7.34%

Oxygen with moisture in fuel = 0.0734 * 16/18 = 0.0652 kg/kg BM

Oxygen with moisture in air supply = 0.01 * 2.771* 16/18 = 0.0246 kg/kg fuel

Total oxygen flow to gasifier with air steam, moisture in fuel and air

= 0.6414 + 0.104 + 0.0652 + 0.0246= 0.8352 kg/kg BM

Hydrogen

Total H_2 in flow to the gasifier with fuel steam, moisture in fuel and moisture in air

= (0.017×2.771) + (0.117× 22/18) + (0.073×2/18) + (0.01× 2.771×2/18)

= 0.07679 kg/kg BM

H_2 associated with H_2& CH_4 in dry gas

= (0.1228 + 0.026 × 2) ×0.152 = 0.0267 kg mol/kg BM

=0.05341 kg H_2 /kg BM

Sulfur

Assuming all S converted to H_2S and removed by the gas cleaning system, hydrogen associated with H_2S in the raw product gas is found to be

=0.0018 × 2/32 = 0.0001125 kg/kg of BM

Total hydrogen in the un cleaned dry product gas including that in H_2S

=0.05341 + 0.0001125 = 0.05353 kg/kg fuel

To find the moisture in the product gas, the hydrogen in dry gas is deducted from the total hydrogen in flow obtained earlier using the hydrogen balance.

= Hydrogen in flow – Hydrogen in dry gas

= 0.07679 –0.05353

= 0.02325 kg/kg of BM

Steam associated with this hydrogen in the gas

=0.02325× 18/2 = 0.2093 kg /kg BM

Oxygen Balance:

Oxygen associated with CO, CO_2 in dry gas which have half a mol and 1 mol of oxygen respectively.

= (0.5 × 0.092 + 0.0778) × 0.1528

= 0.0189 kg mol /kg of BM

= 0.0189× 32 = 0.605 kg /kg of BM

Oxygen associated with the steam in gas

= 0.605× 16/18 = 0.5380 kg /kg of BM

Total Oxygen in gas = 0.605+0.5380 =1.143 kg/kg of BM

Here we note that this is slightly more than the oxygen in flow of 0.8352 kg /kg fuel calculated earlier. This must be due to measurement errors in the given data on fuel gas composition.

Carbon Balance:

Total carbon associated with CO, CO_2 and CH_4 in dry gas whose production rate has been computed earlier as 0.1528 kg.mol / kg fuel is

= (0.092 + 0.0778+ 0.026) × 0.1528

= 0.0299 kg mol/ kg of BM

= 0.3590 kg of C/kg of BM

Carbon conversion efficiency = (0.3590/0.3845)× 100

= 0.9336 = 93.36%

4.4.2 Energy Analysis

Components	Heats of Combustion, MJ/kg mol
CO	282.99
H_2	285.84
CH_4	890.36

Energy output with CO

= 0.092×0.1528(kg mol CO/kg BM) × 282.99 = 2.951MJ/kg fuel

Energy output with H_2

= 0.1228×0.1528(kg mol CO/kg fuel) × 285.84 = 5.36MJ/kg of BM

Energy output with CH_4

= 0.026×0.1528(kg mol CO/kg fuel) × 890.36 = 3.53MJ/kg of BM

Total Energy output = 2.951+5.36+3.53 =11.84 MJ/kg of BM

Total energy input is 16.2 MJ/kg of BM

Cold gas efficiency of the gasifier = (11.84/16.2)×100 = 73.09 %

CHAPTER FIVE

ASPEN PLUS SIMULATION, EXPERIMENTAL OBSERVATIONS AND RESULTS

5.1 ASPEN Plus Simulation

ASPEN Plus simulator is used to model and predict the performance of a process which involves the decomposition of the process into its constituent elements for performance study of individual elements. It is also widely used to study and investigate the effect of various operating parameters on various reactions. (Frederic et al., 2009 and Nikoo etal.,2008)

5.1.1 Assumptions

The following assumptions were considered in modeling in the gasification process

- The gasification process is isothermal and steady state.
- Biomass de-volatilization is instantaneous in comparison to char gasification.
- The biomass particles are spherical and are not affected in course of the reaction.
- All the gases are uniformly distributed within the emulsion phase.
- Char consists of only carbon ash.
- Char gasification starts in the bed and ends in the freeboard.

5.1.2 ASPEN Plus Model

Four different stages considered in ASPEN Plus simulation are decomposition of the feed, volatile reactions, char gasification and gas solid separation.

5.1.3 Biomass Decomposition

The ASPEN Plus yield reactor, RYield was used to simulate the decomposition of the feed. It is used when reaction stoichiometry is unknown or unimportant andreaction kinetic is unknown or unimportant but yield distribution is known.In this step, biomass is converted into its components which include carbon, oxygen,hydrogen, sulfur, nitrogen and ash by specifying the quantities according to its ultimate analysis.

5.1.4 Volatile Reactions

The ASPEN Plus Gibbs reactor, RGibbs, was used for volatile reactions. RGibbs models single phase chemical equilibrium or chemical equilibrium. This model is used when reaction stoichiometry is not known but temperature and pressure of reaction are known. Carbon partly constitutes the gas phase and the remaining carbon comprises part of the solidphase (char) which subsequently undergoes char gasification. A separation column model was used before the RGIBBS reactor to separate volatiles and solids.

5.1.5 Char Gasification

The ASPEN Plus CSTR reactor, RCSTR performs char gasification by using reaction kinetics. RCSTR assumes perfect mixing in the reactor, i.e. the reactor contents have the same properties and composition as the outlet stream.

RCSTR handles kinetic and equilibrium reactions as well as reactions involving solids.That is why RCSTR is preferred for char gasification. The hydrodynamic parameters of the fluidized bed reactor divide the reactor into two regions namely main bed and freeboard region. Each region is simulated by one RCSTR. Parameters considered for RCSTR simulation are listed in Table - 5.1. Components of Rice husk obtained from ultimate and proximate analysis (as listed in Table - 4.2 & Table - 4.3) are used for simulation.

Table - 5.1 (A) Parameters used in the simulation and experimentation

FLUIDIZED BED REACTOR

Temperature (^{o}C)	500 - 700
Pressure (bar)	1.013

AIR

Temperature (^{o}C)	30
Flow rate (m^3/hr)	5 - 20

STEAM

Temperature (^{o}C)	130
Flow rate (kg/hr)	5 - 15

Table -5.1 (B) :GASIFICATION REACTIONS AND THEIR KINETIC PARAMETERS

Reactions	Rate constant($sec^{-1}atm^{-1}$)	Activation energy (kJ/mole of carbon)
$C + H_2O \rightarrow H_2 + CO$	6474.7	13130
$CO_2 + C \rightarrow 2CO$	6474.7	17250
$CO + H_2O \rightarrow CO_2 + H_2$	6474.7	4198
$C + 2H_2 \rightarrow CH_4$	6474.7	7481
$C + 0.5\ O_2 \rightarrow CO$	0.046	110.50
$C + O_2 \rightarrow CO_2$	0.046	393.77

5.1.6 Simulation Flow sheet

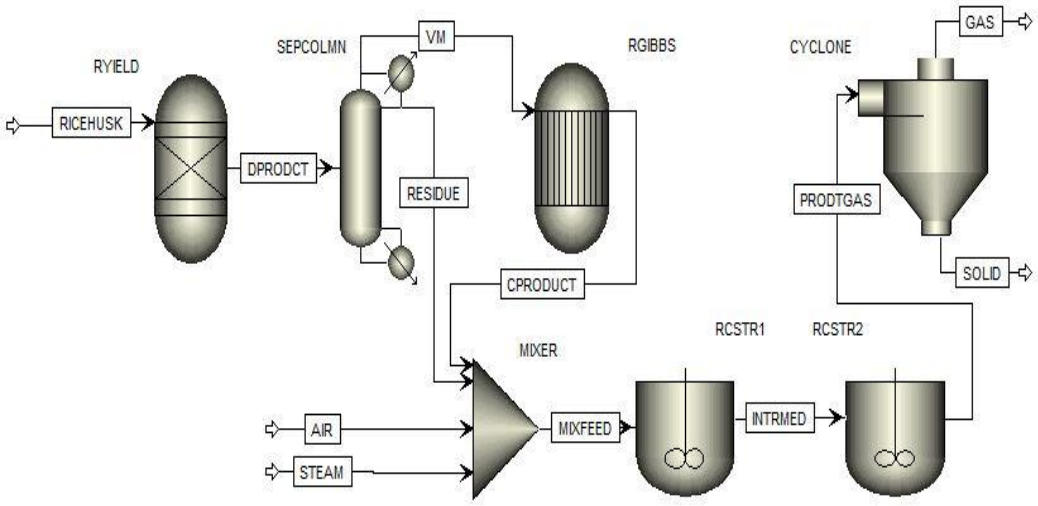


Fig.5.1 Flow sheet of ASPEN Plus Simulation for fluidized bed gasification

5.1.7 Simulation Analysis

Biomass at a rate of 10kg/hr was fed and gasified. The product gas compositions were computed on dry, inert free basis and analyzed with respect to different parameters.

5.1.8 Effect of Temperature

Other parameters such as constant Steam to Biomass Ratio of 0.5, Equivalence Ratio of 0.25 and biomass feed rate of 10 kg/hr were maintained constant. Temperature was only varied. Effect of

temperature on product gas composition was studied by varying temperature within 500-700^{0}C. Observed data are listed in Table - A-1 (Appendix-A). Variation of product gas composition against temperature has been shown in Fig. 5.2

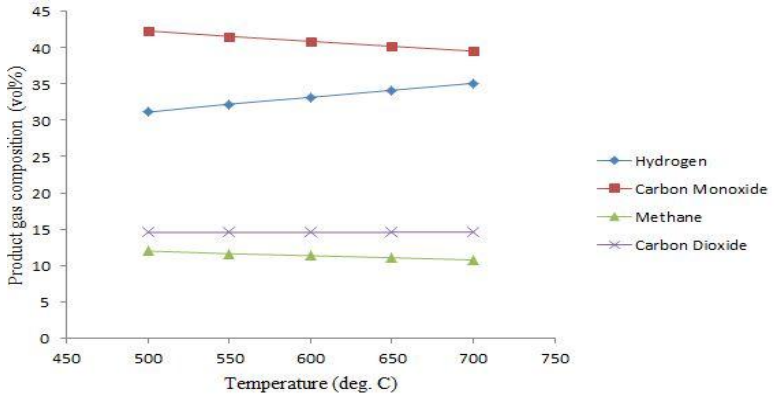


Fig. 5.2 Simulated product gas composition versus temperature

5.1.9 Effect of Equivalence Ratio

Effect of ER on product gas composition was analyzed by varying E.R and keeping constant Steam to Biomass Ratio at 0.5 and constant Temperature at 700^{0}C, Biomass feeding rate at 10 kg/hr. Table - A-2 (Appendix-A) and variation of product gas composition against ER is shown in Fig. 5.3.

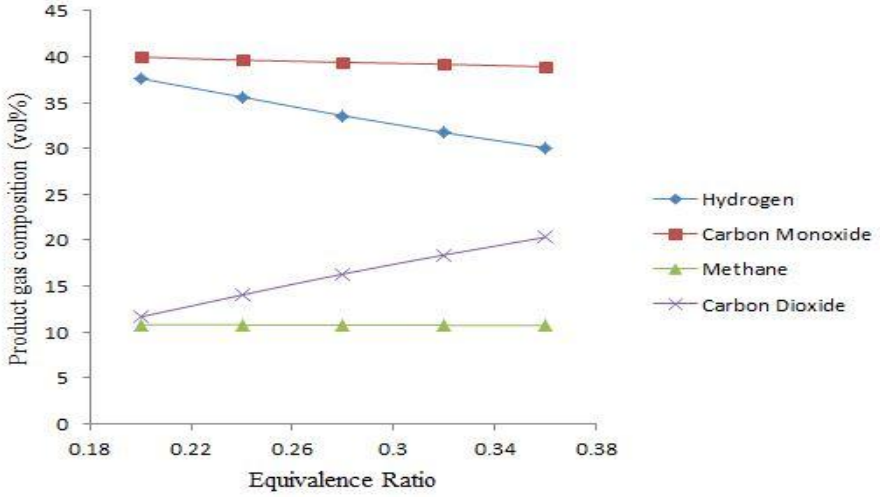


Fig. 5.3 Simulated product gas composition versus equivalence ratio

5.1.10 Effect of Steam to Biomass Ratio

Effect of Steam to Biomass Ratio on product gas composition was studied by varying S/B and keeping other parameters constant.Equivalence ratioof 0.25,Temperature of 700^{0}C and biomass feeding rate of 10kg/hr have been used to study the effect of S/B ratio. The variation in composition of syn-gas with S/B ratio is listed in Table-A-3 (Appendix-A) and shown in Fig. 5.4

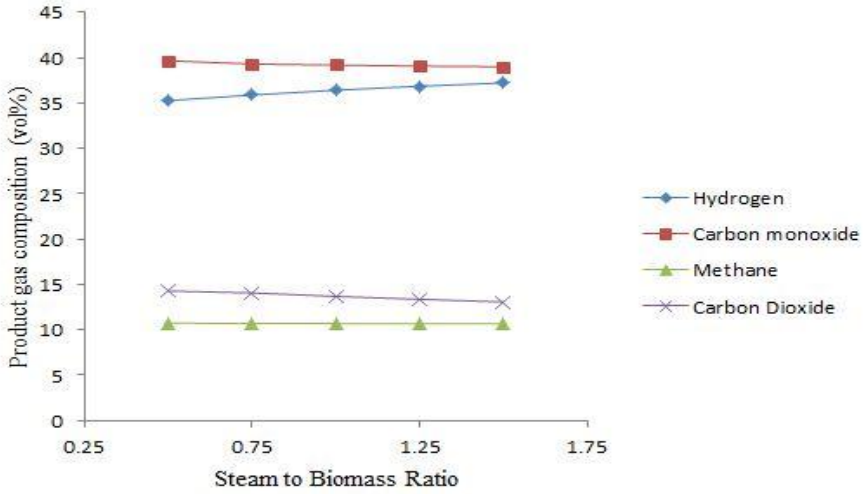


Fig.5.4 Simulated product gas composition versus steam to biomass ratio

5.2 Experimental Observations and Results

It is observed that temperature in the different zones of the gasifier are changing with increase in time during the gasification process which is shown in Table-B-1 (Appendix-B).Temperature profile plot for different zones of gasifier are shown in Fig. 5.5.

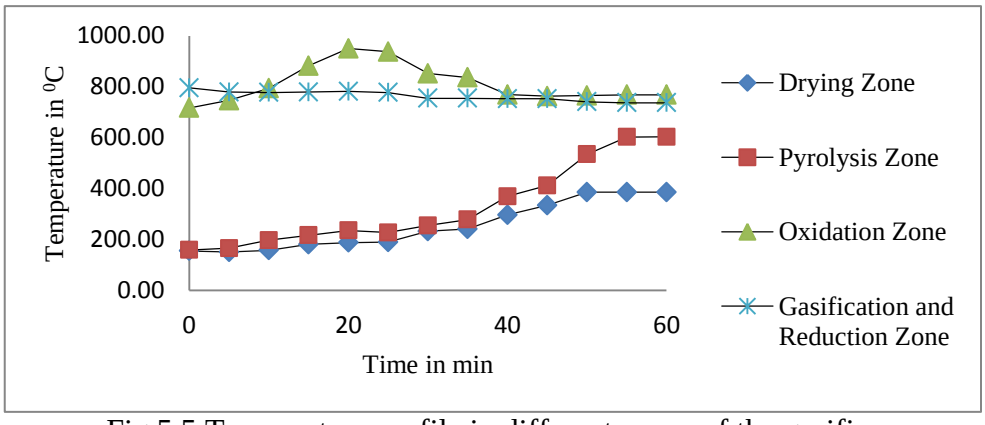


Fig.5.5 Temperature profile in different zones of the gasifier

The product gas from gasifier was analyzed by a Gas analyzer for different feed materials i.e. rice husk,rice straw and saw dust. The observed data are listed in Table-B-2 (Appendix-B) and shown in Fig. 5.6.

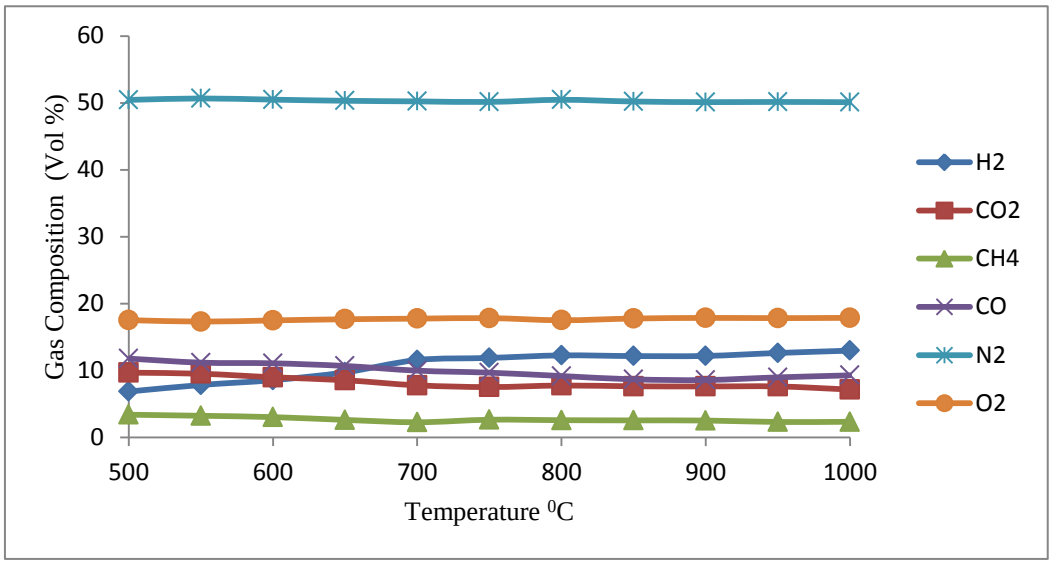


Fig.5.6 Composition of out let gas from gasifier for rice husk as feed material

The observed data obtained from gas analyzer for rice straw are listed in Table – B - 3 (Appendix-B) and shown in Fig .5.7.

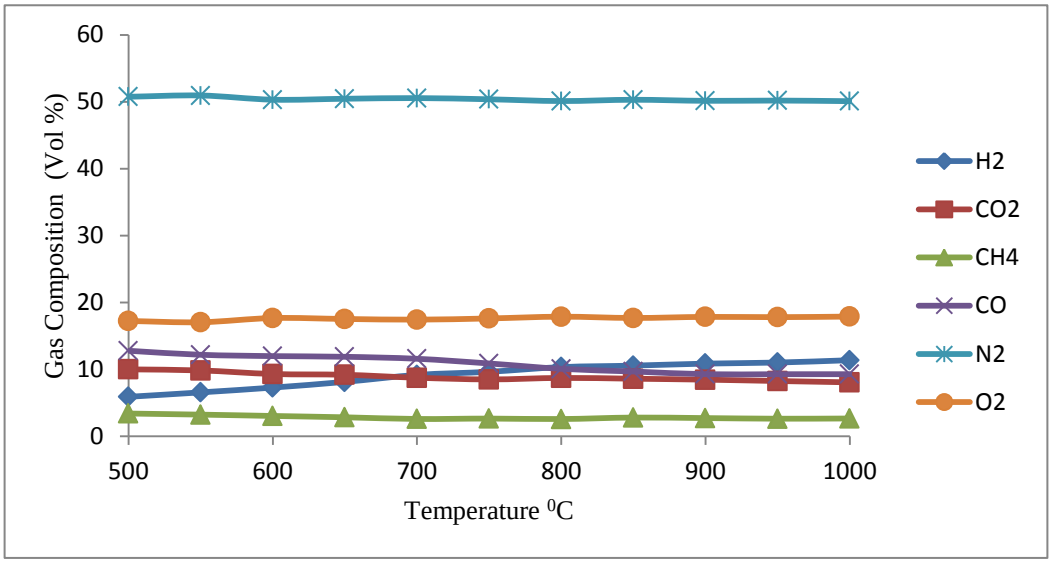


Fig.5.7 Composition of out let gas from gasifier for rice straw as feed material

The observed data obtained from gas analyzer saw dust are listed in Table-B-4 (Appendix-B) and shown in Fig.5.8.

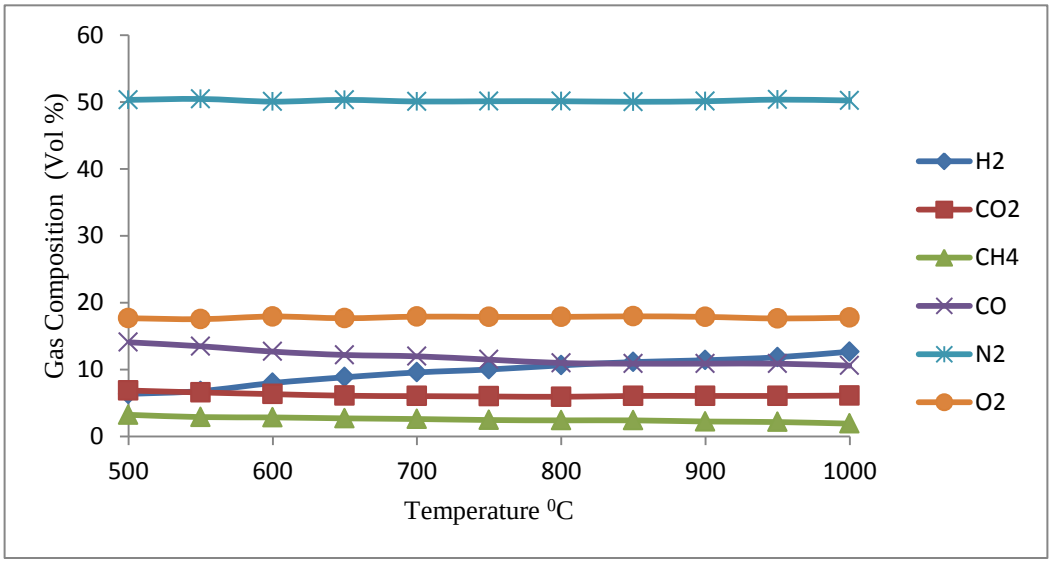


Fig.5.8 Composition of out let gas from gasifier for saw dust as feed material

The syn-gas composition was also computed on N_2 and O_2 free basis for all the feed materials. These are listed in Table-B-5, 6, 7 (Appendix-B). The variation of syn-gas composition against temperature for these materials are shown in Fig.-5.9, 5.10, 5.11 respectively.

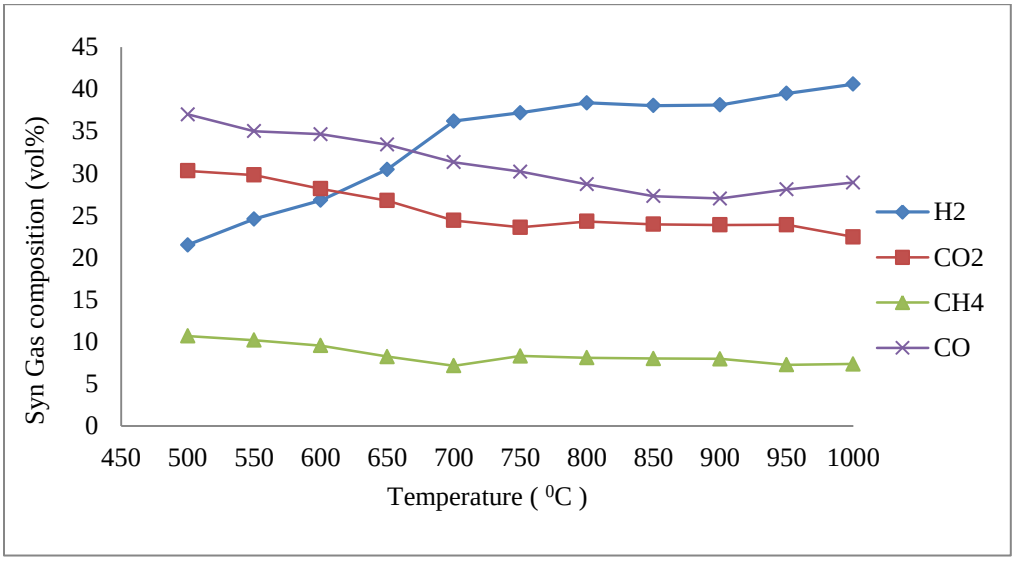


Fig.5.9 Syn-Gas composition for rice husk

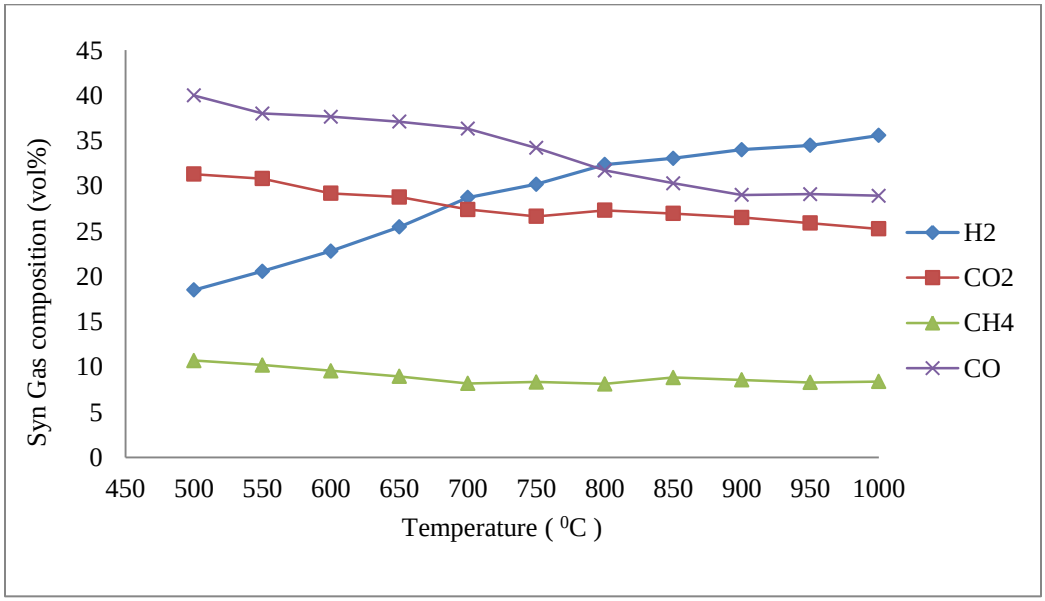


Fig.5.10 Syn-gas composition for rice straw

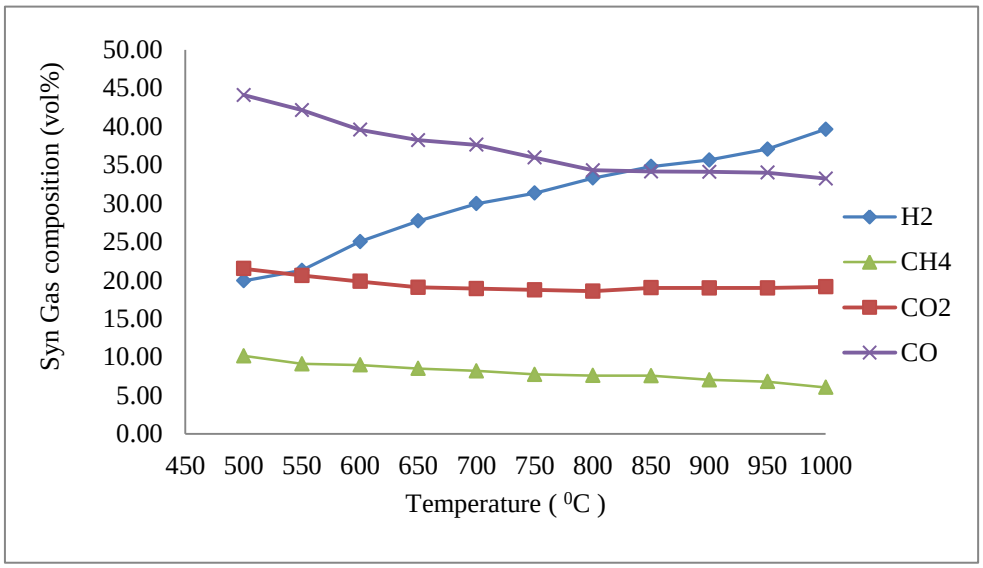


Fig.5.11 Syn-gas composition for saw dust

Effects of temperature on yield of different components for syn-gas have been compared for different feed materials Fig.5.12. Effect of S/B ratio on different components of syn-gas for different feed materials have been studied and listed in Table-B-8, 9, 10 (Appendix-B). The respective plots are shown in Fig., 5.13, 5.14, 5.15. Effect of S/B ratio on yield of syn-gas for different feed materials have been compared individual component wish and shown in Fig.-5.16.Effect of equivalence ratio on different components of syn-gas for different feed materials have been studied and listed in Table-B-11, 12, 13 (Appendix-B). The respective plots are shown inFig.5.17, 5.18, and 5.19. Effect of equivalence ratio on yield of syn-gas for different feed materials have been compared individual component wish and shown in Fig- 5.20.

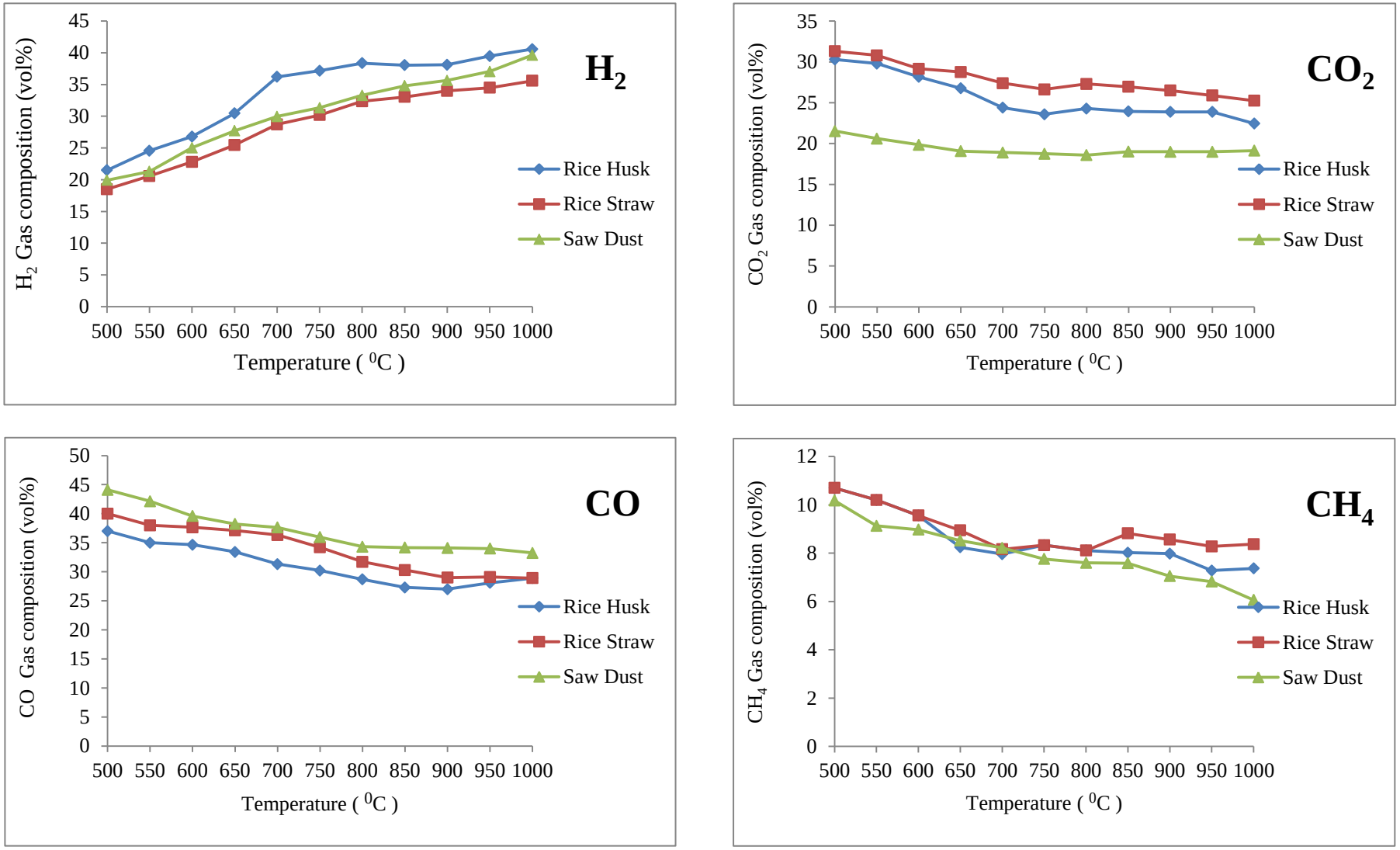


Fig.5.12 Comparison of yield of individual components among different feed material

(S/B= 0, Equivalence Ratio=0.25, Feed Rate 10kg/hr)

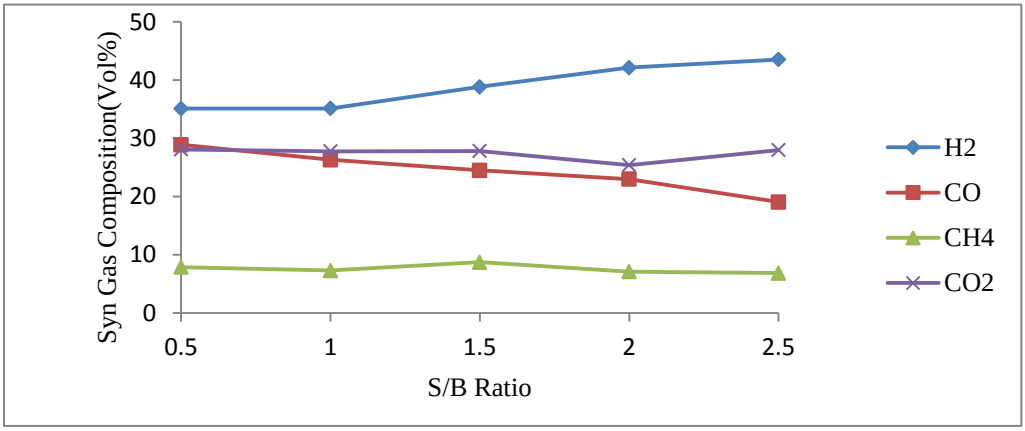


Fig. 5.13 Effect of S/B ratio on syn-gas composition for rice husk

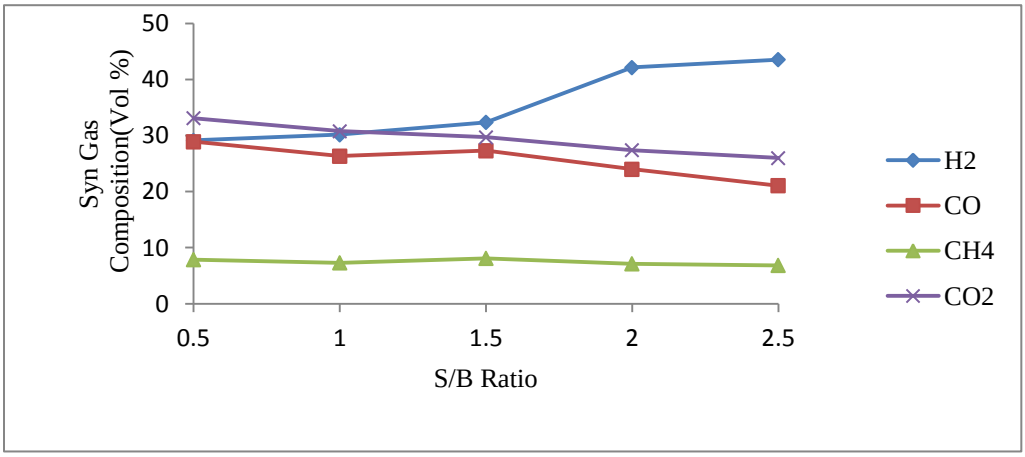


Fig. 5.14 Effect of S/B ratio on syn-gas composition for rice straw

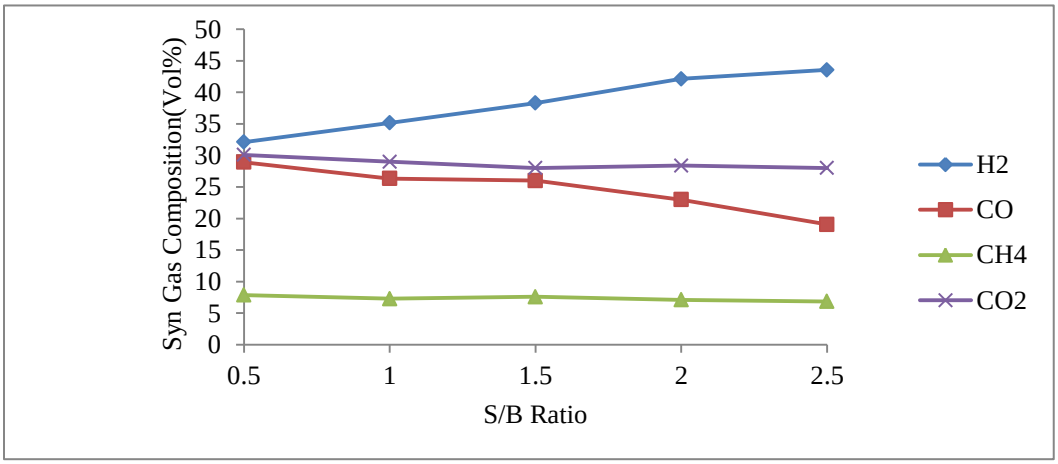
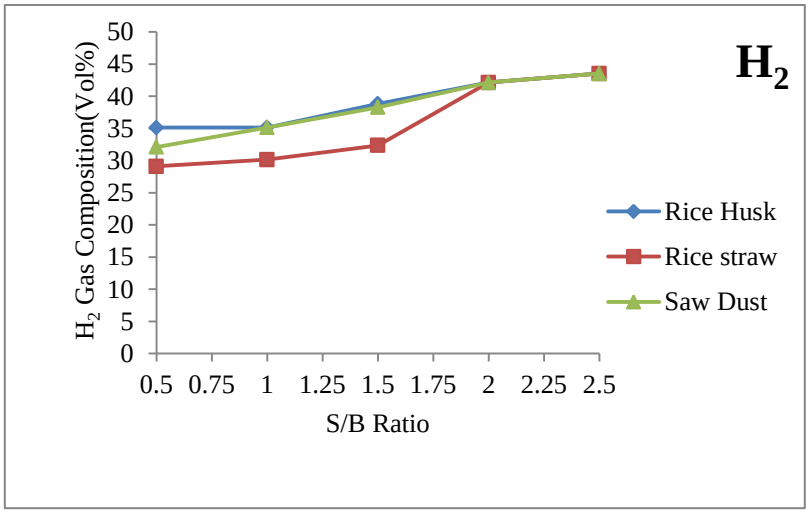
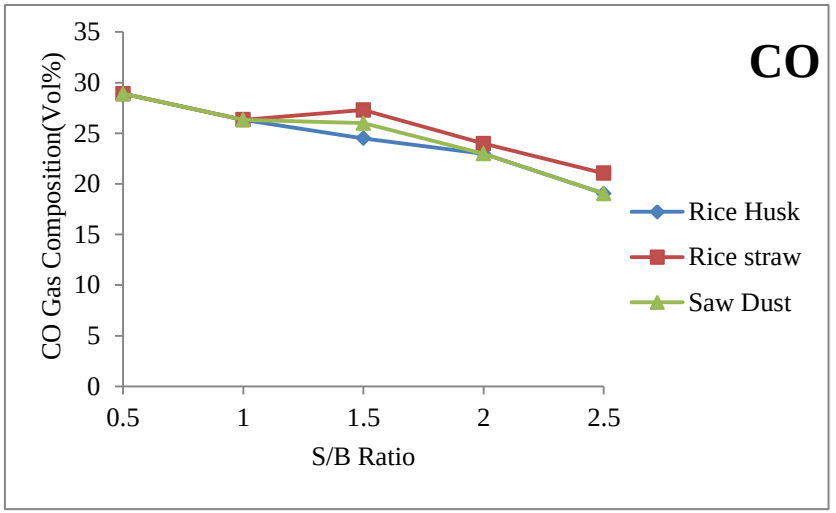
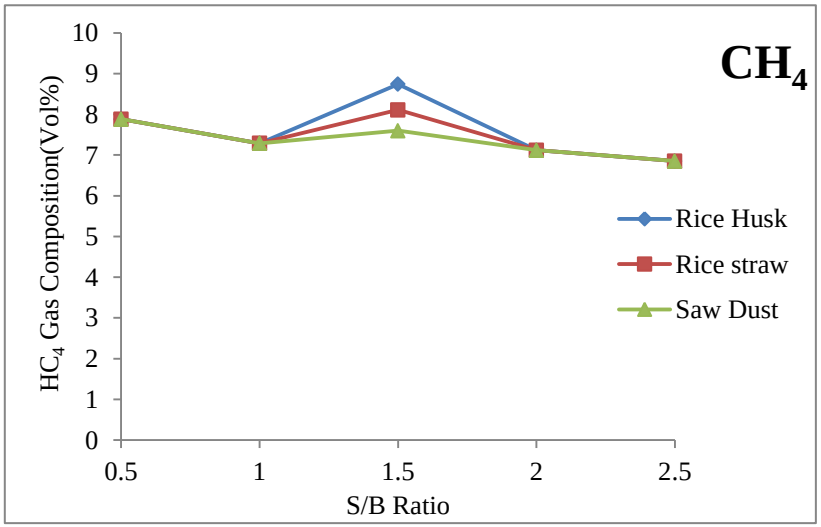


Fig. 5.15 Effect of S/B ratio on syn-gas composition for saw dust







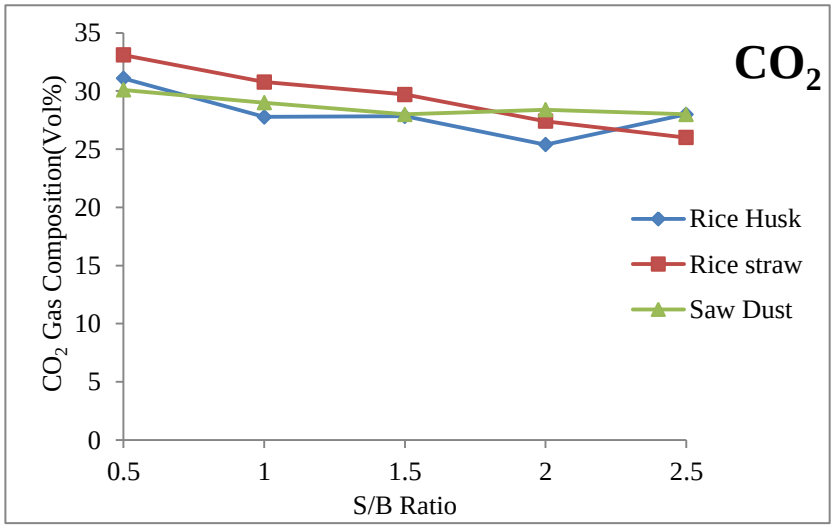


Fig. 5.16 Comparison of effect of S/B ratio on individual components of syn-gas for different feed materials

(Operating temperature=800^{0}C, Equivalence Ratio =0.25, Feed Rate=10kg/hr)

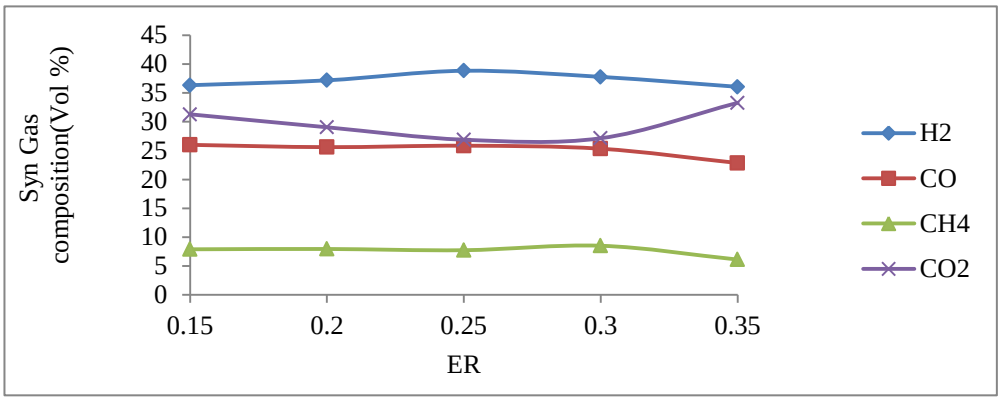


Fig. 5.17 Effect of equivalence ratio on syn-gas composition for rice husk

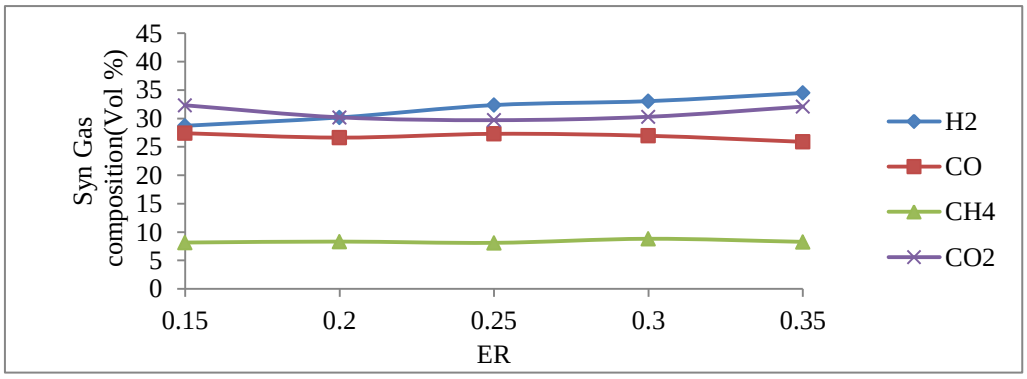


Fig. 5.18 Effect of equivalence ratio on syn-gas composition for rice straw

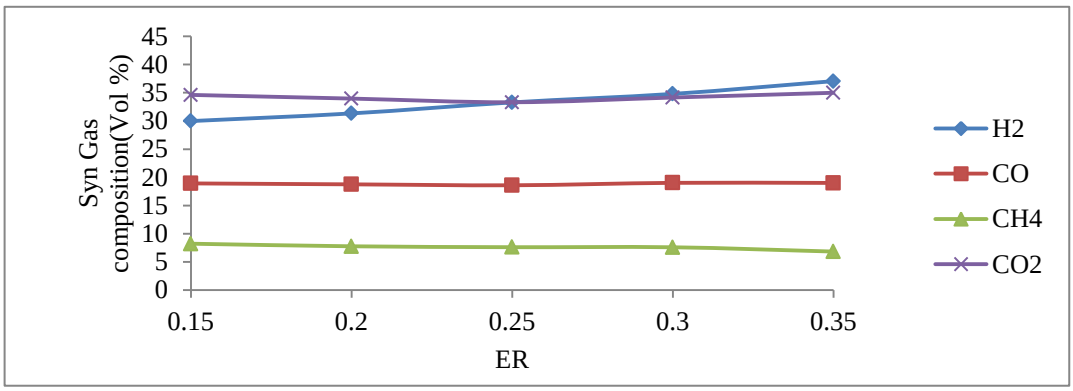


Fig. 5.19 Effect of equivalence ratio on syn-gas composition for saw dust

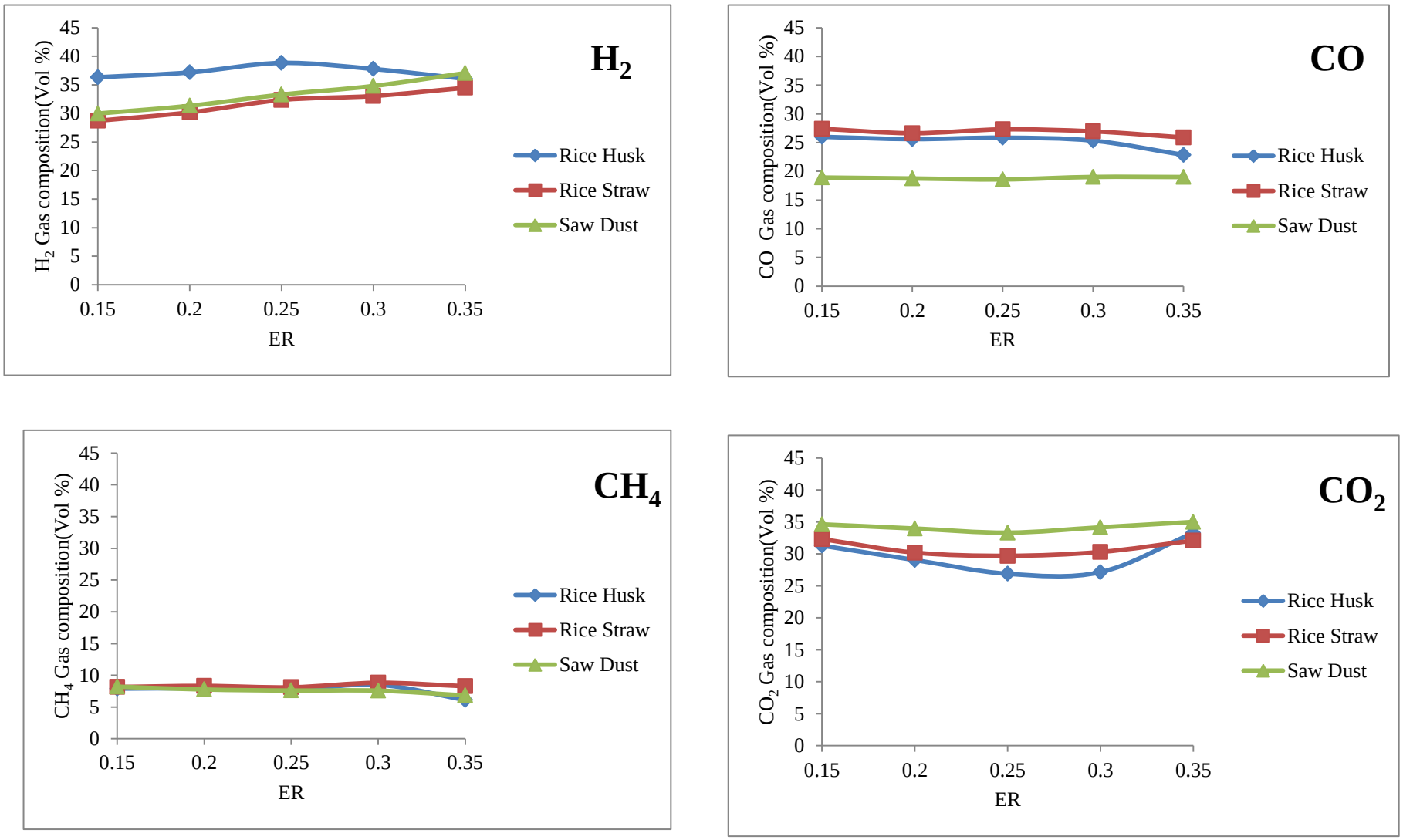


Fig. 5.20 Comparison of effect of equivalence ratio on individual component of syn-gas for different feed materials

(Operating temperature=800^{0}C, Steam to Biomass Ratio =1.5, Feed Rate 10kg/hr)

CHAPTER SIX

DISCUSSION AND CONCLUSION

6.0 Discussions

6.1 Overall Discussion on Results from ASPEN plus Simulation

The effect of different system parameters (viz. temperature,S/B,ER) on the yield of product gas was studied using a fluidized bed gasifier. The experimentally observed data were validated using ASPEN plus simulator. Experimental observations and simulated results were found to be matching in most of the cases. But the concentration of the components were found to be different in some cases.The reason may be the impractical assumptions made for ASPEN plus simulation.

Since gasification is an endothermic reaction, the product gas composition is sensitive towards temperature change. It is observed that the concentration of H_2 increases with increase in temperature. The concentration of CO remains almost constant over theentire range of temperature i.e. 600^0C-900^0C. Higher temperature provides more favorable condition for cracking and steam reforming of methane. Therefore it is observed that the concentration of methane decreases with increase in temperature and there is increase in concentration of hydrogen. The CO_2 concentration decreases with increase in temperature as higher temperature favors endothermic formation of CO from CO_2 via boudouard reaction.

Equivalence ratio is found to be the most important parameter of gasification. The effect of equivalence ratio on product gas composition is studiedin the range 0.2 to 0.36 at 700^0C with steam to biomass ratio of 0.5. The Fig.-5.3 shows that concentration CO_2 is directly proportional to the equivalence ratio. With increase in equivalence ratio, complete combustion of carbon takes place producing more CO_2 and this leads to decrease in concentration of CO. Therefore less H_2 is

produced from water gas shift reaction leading to a decrease in concentration of H_2. Methane concentration remains almost constant over this range of equivalence ratio.

Steam to biomass ratio also plays an important role in gasification of biomass. The effect of steam to biomass ratio on product gas composition was studied over the range of 0.5 - 1.5 at 700^0C with equivalence ratio 0.26. Higher steam to biomass ratio favors more conversion of CO to CO_2 and H_2 through water gas shift reaction.Thus with increase in steam to biomass ratio H_2 and CO_2concentration increases with a decrease in CO concentration in the product gas. Higher steam to biomass also ratio provides more favorable condition for steam reforming of methane. As a result methane concentration decreases with increase in steam to biomass ratio.

6.2 Different Parameter Studied in Experiment Setup

6.2.1Temperature Distribution in the Gasifier

Temperature distribution along the height of the gasifier is shown in Fig. 5.5. From Fig. 5.5 it is found that the feed sample needs a longertime in the drying zone and pyrolysis zone to attain high temperature thanin thecombustion and reduction zones. The reason may be that initially the bed material is at room temperature. Feed along with the air is supplied to the gasifier for proper fluidization before supplying the heat. Thus bed material is dried from room temperature to required temperature and then subjected to pyrolysis. Therefore attainment of high temperature in drying and pyrolysis zones are time taking. But attainment of high temperature in combustion and reduction zone is not time taking as bed material is already at high temperature. At a steadystate temperature of drying zone is about 150^0C - 300^0C, while temperature of the pyrolysis zone remains about 600^0C. The steady temperatures of the pyrolysis zone, combustion zone andreduction zone are 600^0C, 700^0C – 1000^0C and 800^0C, respectively. From the temperature curve of the combustion zone, it is found out that there appears a fluctuation, which

isan occasional phenomenon and possibly caused by O_2 deflagrating because of localaccumulation. Reason may be the use of air as the gasifying agent which is air supplied by a high power blower. This reveals that when a fluidized bed gasifier operates in normal conditions,the flow of air should be changed step by step to avoid a sudden O_2 accumulation andassure operation safety at the startup stage of each run. Besides, a proper distribution of air intakesystem is necessary to make air enter into the gasifier uniformly and avoid local accumulation. As gases flows through the bed and biomass intermixing zone different reactions occur in the different zones. In the drying zone, temperature is about150–300^{0}C. In the pyrolysiszone, temperature is about 600^{0}C, pyrolysis of biomass results in the production of char, tar and gas. In the combustion zone, because of the presence ofoxygen, oxidization reactions of biomass pyrolysis products provides therequired heat for the whole gasification. In the reduction and catalyst zones, secondary reactions of biomass pyrolysis andoxidization products take place, i.e. cracking, reforming and tar decomposition. Nearly all these reactions are endothermic. Therefore the temperature of reduction drops from 800^{0}c to about 600^{0}C in this zone.Thus the design of gasifier leads to a sudden expansion phenomenon which reduces the out let gas temperature up to 45 - 55^{0}C although the gas is allowed to passthrough a high efficiency cyclone separator to separate the dust particles.

6.2.2Effect of Reactor Temperature

It is known thattemperature plays an important role in gasification. In the present work, the reactor temperature is increased from 500 to 1000^{0}C with 50^{0}C increments toinvestigate the effect of temperature on gas compositionand hydrogen yield. The experimental results are presented in Table-B-2, 3, 4 (Appendix-B) and Figure 5.6, 5.7, 5.8 for three different biomass feeds. From Table-B-2, 3, 4 (Appendix-B); it is found out that the H_2 concentrationincreases with

temperature and that the content of CH_4 and CO shows a decreasing trend with increase in temperature which indicates that more CH_4 and CO react with steam to produce additional H_2 through these reactions. As Table-B-2, 3, 4 (Appendix-B) shows, there are still a large quantity of CO in the syn-gas, from which it can be confirmed that shift reaction happens simultaneously in the steam gasification process. Fig.5.12 indicates that under operating condition of S/B = 0 i.e. without steam supply, Equivalence Ratio = 0.25 and Feed Rate = 10kg/hr, hydrogen yield increases from 21.50% to 40.58% for rice husk,18.49 % to 35.55% for rice straw and 19.93 % to 39.64% for saw dust in volume % on N_2 and O_2 free basis.

6.2.3 Effect of Steam-to-Biomass Ratio (S/B)

To study the effect of steam to biomass reaction on hydrogen yield. The steam rate was varied from 0.5 to 2.5 while keeping all other conditions constant as Operating temperature =800^0C, Equivalence Ratio = 0.25 and Feed Rate 10kg/hr. The test results are presented in Table-B-8, 9, 10 (Appendix-B) and Fig.5.13, 5.14, 5.15 for Rice Husk, Rice Straw and Saw Dust respectively. Over an S/B range of 2 to 2.5, hydrogen yield has a nearly linear increase. Syn-gas and hydrogen yield begin to decrease when the S/B exceeds 2.5. This can be justified by the fact that additional low temperature steam fed into the reactor causes the reaction temperature to decrease thereby, causing the gas yield to decrease. Over an S/B range from 1.35 to 2.5, CO concentrations decrease gradually, while the fraction of CO_2 exhibits an opposite trend. This can be explained by the fact that there are more steam reforming reactions of CO and CH_4 taking place because of the added steam.From Table-B-8, 9, 10 (Appendix-B), it can also be found that the hydrogen concentration varies little over this S/B range in which the hydrogen concentration is observed to be decreased with higher S/B. This difference possibly comes from the different operating conditions. From the analysis of the data of varying S/B, it can be agreed that the introduction of

steam in biomass steam gasification does benefit in increasing the gas and hydrogen yields. However, excessive steam will lower the reaction temperature and cause gas and hydrogen yields to decrease as Fig. 5.16 illustrates.

6.2.4 Effect of Equivalence Ratio(ER)

As it is known,equivalence ratio is defined as the actual oxygen-to-fuel ratio divided bythe stoichiometric oxygen-to-fuel ratio needed for completecombustion. In the present study, ER is varied from 0.15 to 0.35 by changing the air flow rate and keeping the other conditions constant as Operating temperature = 800 ^{0}C, Steam to Biomass Ratio =1.5 and Feed Rate 10kg/hr. The test results of varying ER are reported in Table-B-11, 12, 13(Appendix-B) and Fig.5.17, 5.18, 5.19 for Rice Husk, Rice Straw and saw dust respectively.Table-B-11, 12, 13(Appendix-B) indicate that the hydrogen content varied littlein this range of the ER, while gas yield first increases and then decreases with increase in ER. As a result, the hydrogen yield showed the same trend with gas yield as shown in Fig.5.16. ER affects gasification temperature under the condition of auto thermal operation. A higher value of ER corresponds to a higher gasification temperature. In the present work ER is varied from 0.15 to 0.35. Heat is supplied to gasifier initially for which it cannot compensate the heat loss caused by biomass pyrolysis and steam reforming reactions. The operation temperature is not kept constant in the lower part of the reactor. Therefore, the actual temperature of the steamgasification increases as ER is varied from 0.15 to 0.35. Therefore, more gas and hydrogen produced as ER changed from 0.15 to 0.35. Correspondingly, the CO concentration experiences little decrease with almost constant trend as ER increases from 0.15 to 0.35 while the CO_2 concentration shows an opposite trend. When ER is varied from 0.25 to 0.35, oxidation reaction becomes more significant than steam gasification reaction because of the increased oxygen content. Through the above analysis, it is understood

that it is not feasible to apply a too small or a too large ER on biomass air-steam gasification. An ER, too small will lower reaction temperature, which is not favorable for biomass steam gasification. An ER too large will consume the more produced H_2 through the oxidation reaction.

6.3 Conclusion

In general 20% of stoichiometric air is required for gasification which gives certain percentage of efficiency. The increase in stoichiometric air percentage increases the percentage of efficiency. Varying the types of wood also affects the percentage of efficiency. Therefore by varying the percentage of stoichiometric air and wood the performance of gasifier can be studied and thus the gasification efficiency can be optimized. Biomass gasification offers the most attractive alternative energy system. Most preferred fuels for gasification have been charcoal and biomass. However biomass residues are the most appropriate fuels for on-farm systems and offer the greatest challenge to researchers and gasification system manufacturers. Most extensively used and researched systems have been based on downdraft gasification. However it appears that for fuels with high ash content fluidized bed combustion may offer abetter solution. At present no reliable and economically feasible system exists. Biggest challenge of gasification systems lies in developing a reliable and economical gas purification system. The increase of air supply up to certain percentage reduces the percentage of char content and increase the temperature of the producer gas. The increase of air supply up to certain percentage thus increases the percentage of CH_4 which contains more colorific value. Thus using biomass as fuel will cause no damage to the environment.

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List of Tables

Appendix -A

Simulation Results

Table-A-1 Simulated product gas composition (volume %) at different temperatures

Temp(^{o}C)	H_2 (vol%)	CO (vol%)	CH_4 (vol%)	CO_2 (vol%)
500	31.12	42.34	11.99	14.55
550	32.24	41.58	11.62	14.56
600	33.18	40.9	11.35	14.57
650	34.15	40.21	11.06	14.58
700	35.11	39.56	10.76	14.59

Table-A-2 Simulated product gas composition (volume %) at different equivalence ratio

ER	H_2 (vol%)	CO (vol%)	CH_4 (vol%)	CO_2 (vol%)
0.20	37.61	39.97	10.79	11.63
0.24	35.61	39.62	10.76	14.01
0.28	33.56	39.39	10.74	16.31
0.32	31.72	39.18	10.72	18.38
0.36	30.07	38.91	10.71	20.31

Table-A-3Simulated product gas composition (volume %) at different steam to biomass ratios

S/B ratio	H_2 (vol%)	CO (vol%)	CH_4 (vol%)	CO_2 (vol%)
0.50	35.28	39.68	10.75	14.29
0.75	35.89	39.32	10.72	14.07
1.00	36.42	39.19	10.70	13.69
1.25	36.86	39.08	10.69	13.37
1.50	37.22	39.01	10.69	13.08

Appendix -B

Experimental Results

Table-B-1 Variation of temperature inside the gasifier

Temperature Profile				
Time (min)	Drying Zone ^{0}C	Pyrolysis Zone ^{0}C	Oxidation Zone ^{0}C	Gasification and Reduction Zone ^{0}C
0	155.07	159.16	716.91	795.36
5	151.07	165.74	746.80	778.93
10	157.60	197.59	793.45	777.00
15	181.07	216.77	882.34	779.27
20	187.69	235.94	950.05	781.52
25	190.02	227.69	937.21	777.49
30	232.55	255.33	851.93	754.74
35	241.11	278.62	836.28	754.81
40	296.35	369.66	769.14	752.98
45	334.61	411.95	762.92	753.05
50	385.59	534.64	765.21	740.64
55	385.88	602.56	768.25	736.84
60	386.12	602.95	768.26	737.02

Table-B-2 Product gas composition obtained from analyzer with N_2 and O_2 for rice husk (S/B= 0,Without steam, Equivalence=0.25, Feed Rate=10kg/hr)

Temp(^{o}C)	H_2	CO_2	CH_4	CO	N_2 and Other Gases	O_2
500	6.88	9.70	3.42	11.8	50.45	17.55
550	7.86	9.54	3.26	11.2	50.67	17.33
600	8.58	9.01	3.06	11.1	50.49	17.51
650	9.75	8.57	2.64	10.7	50.32	17.68
700	11.59	7.81	2.29	10.0	50.23	17.77
750	11.90	7.55	2.67	9.7	50.15	17.85
800	12.28	7.78	2.60	9.2	50.47	17.53
850	12.18	7.66	2.57	8.7	50.21	17.79
900	12.20	7.64	2.55	8.6	50.12	17.88
950	12.64	7.64	2.33	9.0	50.15	17.85
1000	12.99	7.18	2.36	9.3	50.11	17.89

Table- B-3 Product gas composition obtained from analyzer with N_2 and O_2 for rice straw (S/B= 0, Equivalence=0.25, Feed Rate =10 kg/hr)

Temp(^oC)	H_2	CO_2	CH_4	CO	N_2 and Other Gases	O_2
500	5.92	10.02	3.42	12.8	50.75	17.25
550	6.58	9.86	3.26	12.2	50.94	17.06
600	7.30	9.33	3.06	12.0	50.31	17.69
650	8.15	9.21	2.86	11.9	50.45	17.55
700	9.19	8.77	2.61	11.6	50.55	17.45
750	9.66	8.52	2.67	10.9	50.37	17.63
800	10.36	8.74	2.60	10.1	50.11	17.89
850	10.58	8.62	2.82	9.7	50.3	17.7
900	10.88	8.48	2.74	9.3	50.14	17.86
950	11.04	8.28	2.65	9.3	50.18	17.82
1000	11.39	8.08	2.68	9.3	50.09	17.91

Table- B-4 Product gas composition obtained from analyzer with N_2 and O_2 for saw dust (S/B = 0, Equivalence = 0.25, Feed Rate =10kg/hr)

Temp(^oC)	H_2	CO_2	CH_4	CO	N_2 and Other Gases	O_2
500	6.38	6.89	3.26	14.1	50.31	17.69
550	6.81	6.60	2.92	13.5	50.45	17.55
600	8.01	6.35	2.87	12.7	50.05	17.95
650	8.87	6.11	2.73	12.2	50.31	17.69
700	9.59	6.05	2.63	12.0	50.07	17.93
750	10.03	6.00	2.48	11.5	50.11	17.89
800	10.65	5.95	2.43	11.0	50.11	17.89
850	11.14	6.08	2.43	10.9	50.03	17.97
900	11.41	6.08	2.26	10.9	50.11	17.89
950	11.86	6.08	2.18	10.9	50.35	17.65
1000	12.69	6.13	1.94	10.6	50.22	17.78

Table- B-5 Syn-gas composition on N_2 and O_2 free basis for rice husk

(S/B= 0, Equivalence Ratio =0.25, Feed Rate =10kg/hr)

Temp(^oC)	H_2	CO_2	CH_4	CO	NHV kcal/m^3
500	21.5	30.3	10.7	37	2382.78
550	24.57	29.8	10.2	35	2403.76
600	26.8	28.17	9.56	34.65	2357.10
650	30.46	26.77	8.24	33.41	2295.84
700	36.21	24.4	7.16	31.32	2279.63
750	37.18	23.6	8.33	30.2	2380.71
800	38.36	24.3	8.11	28.7	2413.28
850	38.05	23.95	8.02	27.3	2387.05
900	38.12	23.88	7.98	27.01	2383.3132
950	39.49	23.89	7.28	28.09	2358.83
1000	40.58	22.45	7.37	28.91	2351.16

Table- B-6 Syn-Gas composition on N_2 and O_2 free basis for rice straw

(S/B= 0, Equivalence=0.25, Feed Rate=10kg/hr)

Temp(^oC)	H_2	CO_2	CH_4	CO	NHV Kcal/m^3
500	18.5	31.30	10.7	40	2335.82
550	20.57	30.80	10.2	38	2331.10
600	22.8	29.17	9.56	37.65	2284.44
650	25.46	28.77	8.94	37.11	2287.61
700	28.71	27.40	8.16	36.32	2263.00
750	30.18	26.63	8.33	34.2	2292.14
800	32.36	27.30	8.11	31.7	2349.50
850	33.05	26.95	8.82	30.3	2417.53
900	34.00	26.50	8.56	29.00	2406.10
950	34.49	25.89	8.28	29.09	2376.31
1000	35.58	25.25	8.37	28.91	2392.75

Table- B-7 Syn-gas composition on N_2 and O_2 free basis for saw dust
(S/B= 0, Equivalence=0.25, Feed Rate=10kg/hr)

Temp(^oC)	H_2	CO_2	CH_4	CO	NHV Kcal/m^3
500	19.93	21.52	10.18	44.10	2713.63
550	21.29	20.61	9.13	42.15	2600.12
600	25.03	19.85	8.97	39.60	2605.70
650	27.72	19.08	8.52	38.24	2595.15
700	29.98	18.92	8.21	37.62	2608.39
750	31.34	18.75	7.76	35.97	2554.36
800	33.29	18.58	7.60	34.32	2541.20
850	34.80	19.01	7.58	34.16	2573.80
900	35.65	19	7.05	34.11	2548.4654
950	37.06	19.00	6.82	34.00	2561.85
1000	39.64	19.14	6.06	33.24	2540.18

Table- B-8 Effect of steam/biomass ratio on syn-gas composition for rice husk
(Operating temperature=800^0C, Equivalence Ratio =0.25, Feed Rate =10kg/hr)

S/B Ratio	H_2	CO	CH_4	CO_2
0.5	35.12	28.91	7.88	28.1
1	35.15	26.33	7.29	27.78
1.5	38.83	24.50	8.74	27.83
2	42.14	22.98	7.12	25.40
2.5	43.54	19.05	6.85	28.02

Table-B-9 Effect of steam/biomass ratio on syn-gas composition for rice straw
(Operating temperature=800 ^{0}C, Equivalence Ratio =0.25, Feed Rate =10kg/hr)

S/B Ratio	H_2	CO	CH_4	CO_2
0.5	29.12	28.91	7.88	33.1
1	30.15	26.33	7.29	30.78
1.5	32.36	27.30	8.11	29.7
2	42.14	23.98	7.12	27.4
2.5	43.54	21.05	6.85	26

Table-B-10 Effect of steam/biomass ratio on syn-gas composition for saw dust
(Operating temperature=800^{0}C, Equivalence Ratio =0.25, Feed Rate =10 kg/hr)

S/B Ratio	H_2	CO	CH_4	CO_2
0.5	32.12	28.91	7.88	30.1
1	35.15	26.33	7.29	29
1.5	38.29	26.00	7.60	28.00
2	42.14	22.98	7.12	28.4
2.5	43.54	19.05	6.85	28

Table-B-11 Effect of equivalence ratio on syn-gas composition for rice husk
(Operating temperature=800 ^{0}C, Steam.to Biomass Ratio =1.5, Feed Rate =10kg/hr)

Equivalence Ratio	H_2	CO	CH_4	CO_2
0.15	36.33423	26	7.89518	31.28994
0.2	37.17677	25.6	7.950612	29.04268
0.25	38.8393	25.85	7.74116	26.887
0.3	37.77858	25.33	8.51177	27.14338
0.35	36.05569	22.85	6.1147	33.28274

Table-B-12 Effect of equivalence ratio on syn-gas composition for rice straw
(Operating temperature=800^{0}C, Steam.to Biomass Ratio =1.5, Feed Rate= 10 kg/hr)

Equivalence Ratio	H_2	CO	CH_4	CO_2
0.15	28.71	27.40	8.16	32.32
0.2	30.18	26.63	8.33	30.2
0.25	32.36	27.30	8.11	29.7
0.3	33.05	26.95	8.82	30.3
0.35	34.49	25.89	8.28	32.09

Table-B-13 Effect of equivalence ratio on syn-gas composition for saw dust
(Operating temperature=800^{0}C, Steam.to Biomass Ratio =1.5, Feed Rate=10 kg/hr)

Equivalence Ratio	H_2	CO	CH_4	CO_2
0.15	29.98	18.92	8.21	34.62
0.2	31.34	18.75	7.76	33.97
0.25	33.29	18.58	7.60	33.32
0.3	34.80	19.01	7.58	34.16
0.35	37.06	19.00	6.82	35.00